Simulated In Situ Measurements and Structural Analysis of Reconnection-Driven Solar Polar Jets

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Introduction

Solar polar jets are observed to originate in regions within the open field of solar coronal holes. They are associated with an embedded dipole topology, consisting of a fan-separatrix and a spine line emanating from a null point occurring at the top of the dome shaped fan surface (Antiochos,1998).

In this study, we analyze simulations using the Adaptively Refined MHD Solver (ARMS) that take into account gravity, solar wind, and spherical geometry to generate polar jets by reconnection between a twisted embedded bipole and the surrounding open field (Karpen et al. 2015). These new simulations confirm and extend previous Cartesian studies of polar jets based on this mechanism (Pariat et al. 2009, 2010, 2015).

Focusing on the plasma density, velocity, and magnetic field, we interpolate the adaptively gridded simulation data onto a regular grid, and analyze the signatures that the jet produces as it propagates outward from the solar surface. The trans-Alfvénic nature of the jet front is confirmed by temporally differencing the plasma mass density and comparing the result with the local Alfvén speed. We perform a preliminary analysis of the magnetized plasma turbulence, and examine how the turbulence affects the overall structure of the jet. We also conduct simulated spacecraft fly-throughs of the jet, illustrating the signatures that spacecraft such as Solar Probe Plus may encounter in situ as the jet propagates into the heliosphere. These fly-throughs are performed in several different velocity regimes to better model the changing velocity of Solar Probe Plus relative to the Sun and its jets over the course of the mission.

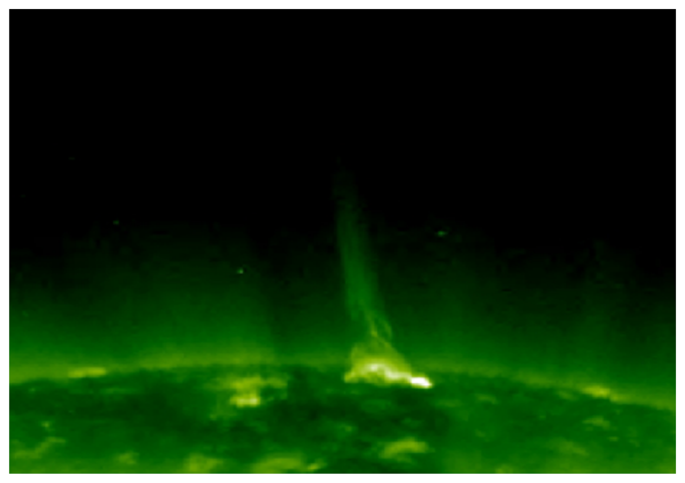


Fig. 1. An observed polar jet propagating into the Heliosphere as seen by the *STEREO* EUVI/COR instrument. (Patsourakos et al. 2008)

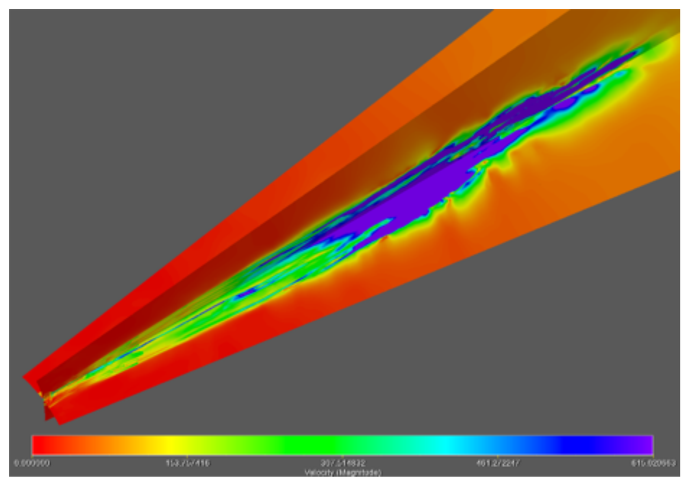


Fig. 2. Visualization of |**V**| near the end of the simulation.

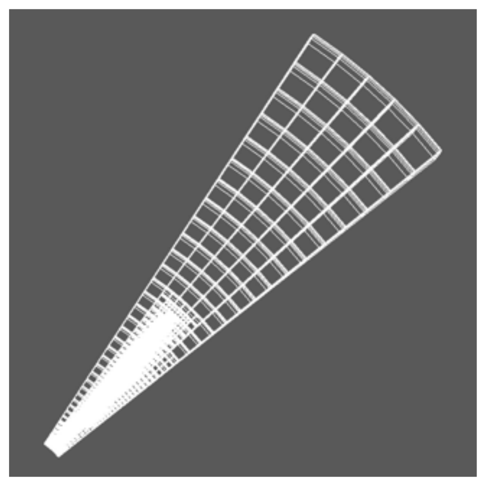


Fig. 3. Visualization of the ARMS adaptive grid.

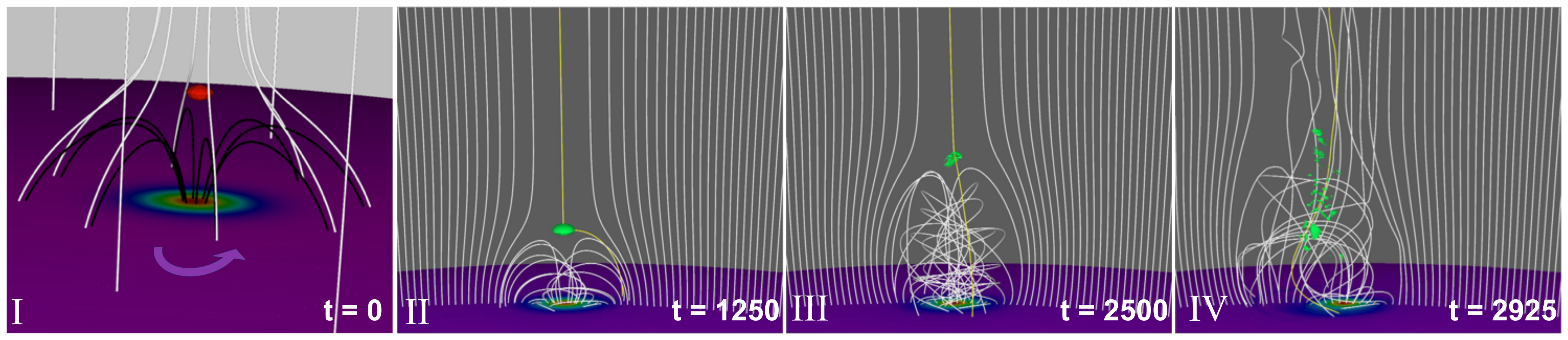


Fig. 4. Images from the ARMS model run. **I.** A dome-shaped fan surface separates closed (*black*) from open (*white*) magnetic field lines with a null point (*red*); twisting flows (*magenta arrow*) energize the field. **II.** The energy build-up phase. **III.** Just before the reconnection. **IV.** The reconnection driven energy transfer phase.

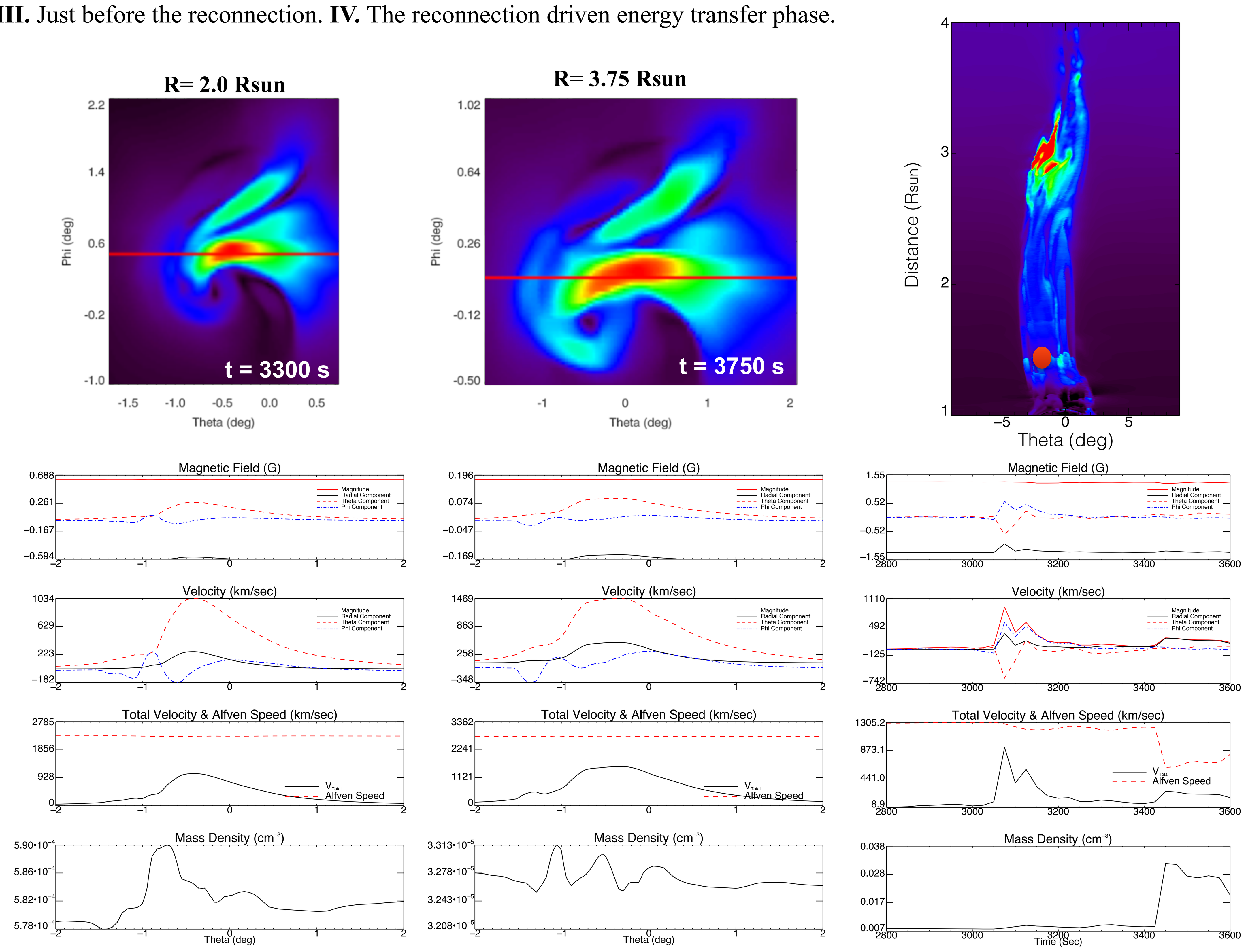
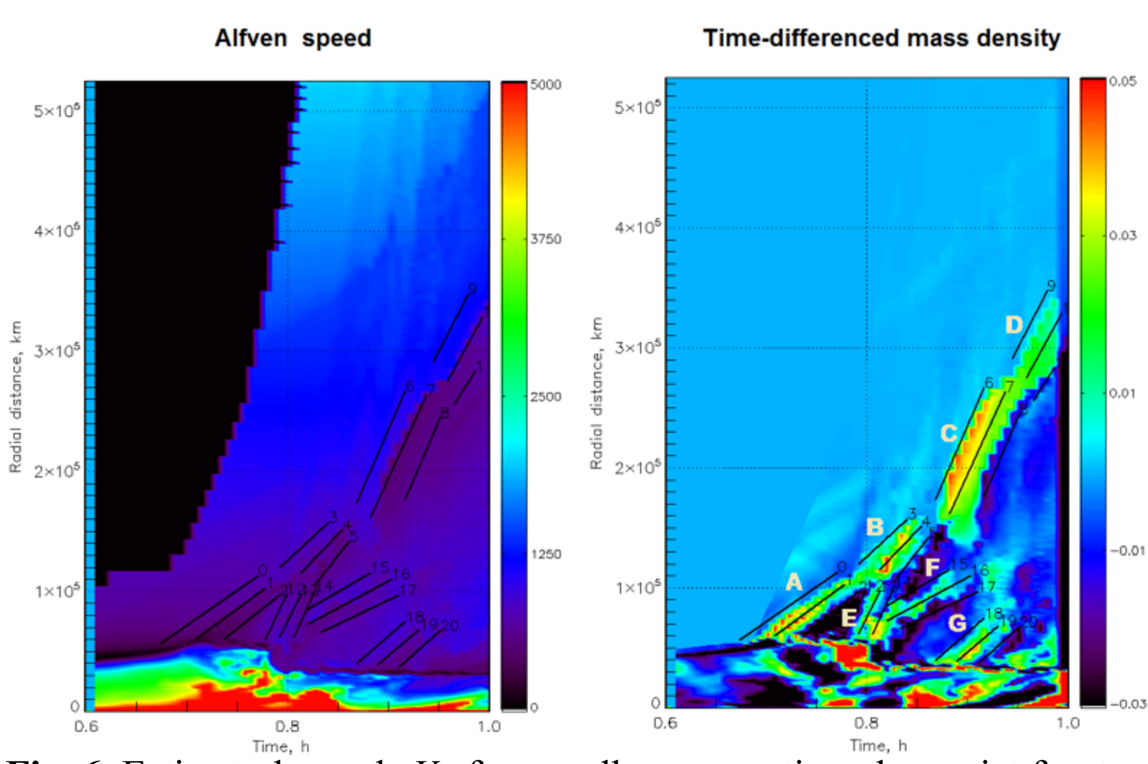


Fig. 5. Simulated flyby trajectories with the resultant one dimensional variable measurements directly below them. The first two show same the structure flown through twice (in a realm where $V_{jet} << V_{probe}$) at different times and radial distances as it propagated outward from the reconnection site. It appears to maintain its morphology as the jet expands and propagates radially. The third illustrates the case where $V_{jet} >> V_{probe}$, such that the entire jet propagates past the spacecraft while it remains approximately stationary. The image shown is a single time step from the end of the simulation run, and the red circle represents the approximate spacecraft position.



Front ID and edge indices	V / $\langle V_A \rangle$ / $V_{A,\min}$ (km/s)		
	Leading edge	Front interior	Trailing edge
A (0-2)	162 / 609 / 343	172 / 517 / 281	184 / 558 / 458
B (3-5)	216 / 825 / 795	238 / 663 / 546	286 / 617 / 581
C (6-8)*	**534 / 1036 /904**	**509 / 614 / 507**	**546 / 639 / 614**
D (9-11)	454 /1236 /1172	428 / 710 / 582	364 / 650 / 622
E (12-14)*	**504 / 730 / 617**	**462 / 828 / 770**	**518 / 651 / 580**
F (15-17)	135 / 799 / 672	126 / 714 / 591	111 / 766 / 672
G (18-20)	198 / 884 / 841	196 / 721 / 613	203 / 748 / 603

Fig. 6. Estimated speeds V of upwardly propagating plasma jet fronts as compared with the average ($\langle V_A \rangle$) and minimum ($V_{A,\min}$) Alfvén speeds along the leading and the trailing edges of the front as well as inside the front. The fronts are identified using temporal differencing of plasma mass density position-time plots.

$$\delta B_l = (\boldsymbol{B}(\boldsymbol{r}+\boldsymbol{l}) - \boldsymbol{B}(\boldsymbol{r}))\cdot \boldsymbol{l}/l, \quad S_q(l) = \langle |\delta B_l|^q \rangle$$

$$\boxed{S_q(l) \sim l^{\zeta(q)}}$$

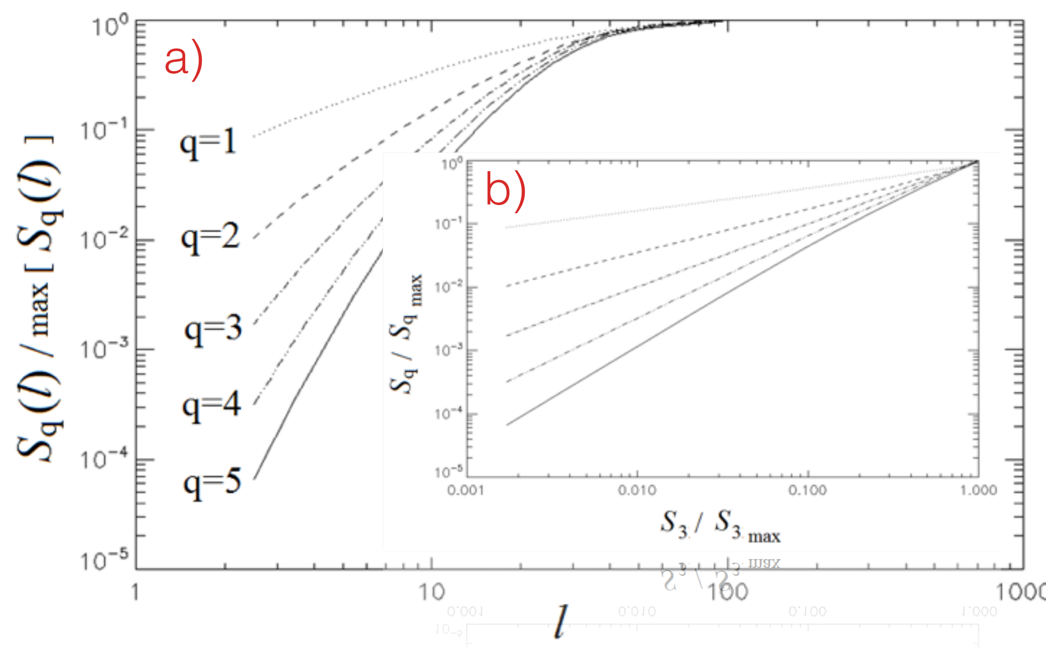
$\zeta(q)$ – defined by the turbulent regime:

$$\boxed{\zeta(q) = (1-\gamma)q/g + C(1 - [1-\gamma/C]^{q/g})}$$

$\delta v \sim \ell^{1/g} \qquad t_e \sim \ell^{\gamma}$

t_e – energy transfer time at smallest inertial scale ℓ

C – codimension of dissipative structures



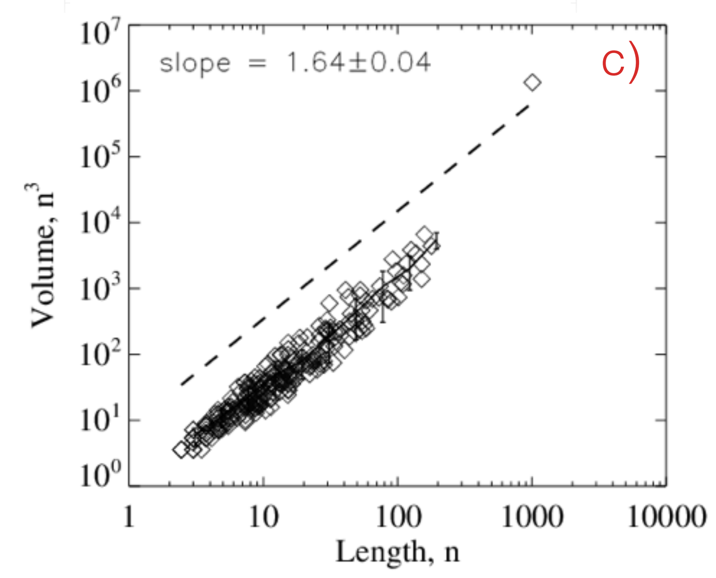
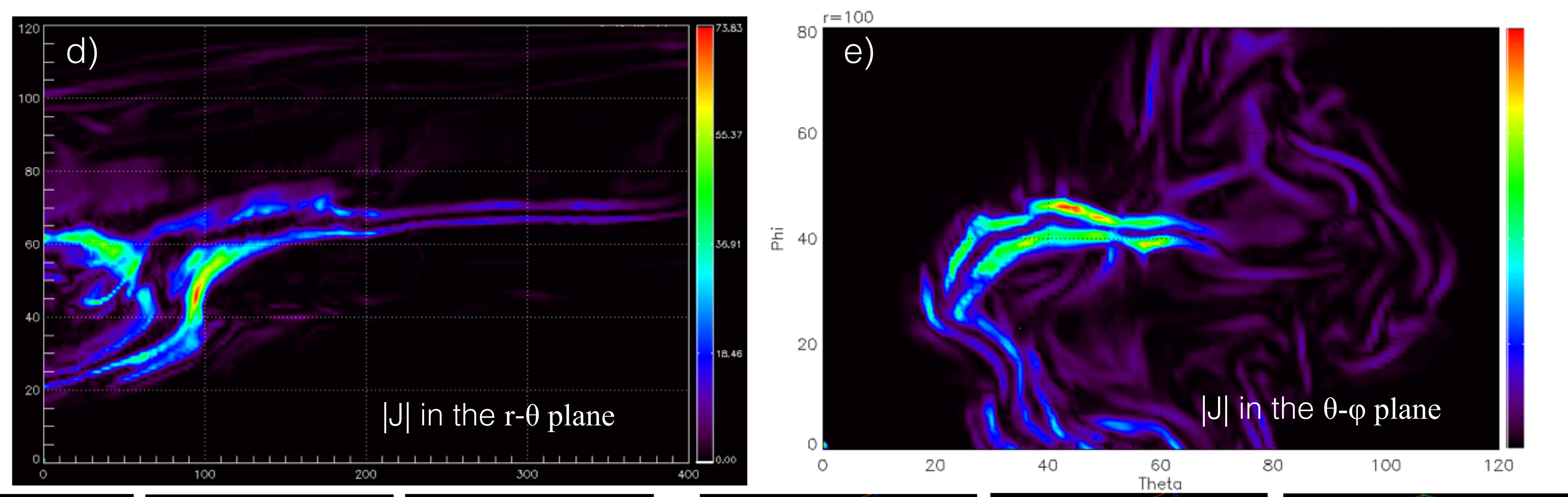
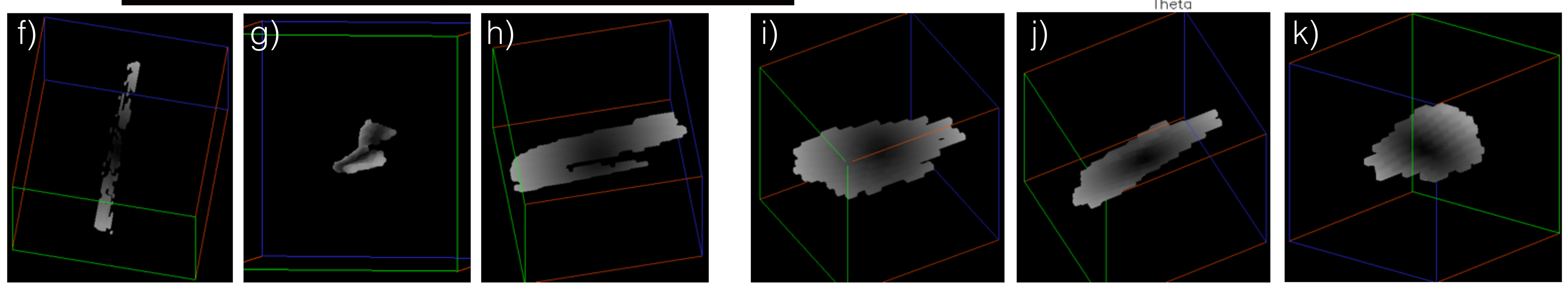


Fig. 7. Turbulence Analysis: **a)** Structure functions of the magnetic field. The observed departure from the power-laws is due to the relatively low magnetic Reynolds number (<102) of the run. **b)** Extended self-similarity normalization to recover the scaling of the structure functions. **c)** Volumes of current density structures vs their linear sizes. The power-law exponent of 1.64 suggests that the structures are quasi-two dimensional with irregular edges. **(d-e)** Total current density (|J|) in the jet shown in both a radial and transverse cut. **(f-k)** Current density structures (contiguous spatial regions with current density above a detection threshold) exhibiting a sheet-like 2D geometry. **f)** shows all the current sheets in the jet, **g) & h)** the same structure from two different angles, and **i), j) & k)** a single structure from three different angles.





Concluding Remarks

- The jets have a complex underlying structure, including some fronts which appear to approach the local Alfvén speed.
- The jet is accompanied by a pronounced magnetic turbulence across the entire range of altitudes studied.
- Simulated Flybys show jet structures maintaining their integrity as the propagate radially outward despite this turbulence, illustrating the possibility that they persist into regions where they could be measured by Solar Probe Plus (~ 9 solar radii)
- The autocorrelation structure of the turbulence is consistent with the MHD turbulence model, implying 2D dissipative structures (as opposed to 1D eddies in hydrodynamic turbulence models).
- The dimensionality of the dissipative structures is confirmed by direct analysis of current density field revealing numerous current sheets.

Future Goals

- Extend the simulation volume to distances that could be directly encountered by Solar Probe Plus. (See Karpen et al. Poster 203.03)
- Simulate *in situ* spacecraft measurements where the jet and spacecraft speeds are of the same order of magnitude.
- The alignment and cylindrical geometry of the current sheets suggests that the turbulence in this simulation is formed by torsional Alfvén waves. Further investigation is needed to clarify the role of these waves.

Acknowledgements

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